AS Unit BY2: Biodiversity and Physiology of Body Systems

Name:	Date:

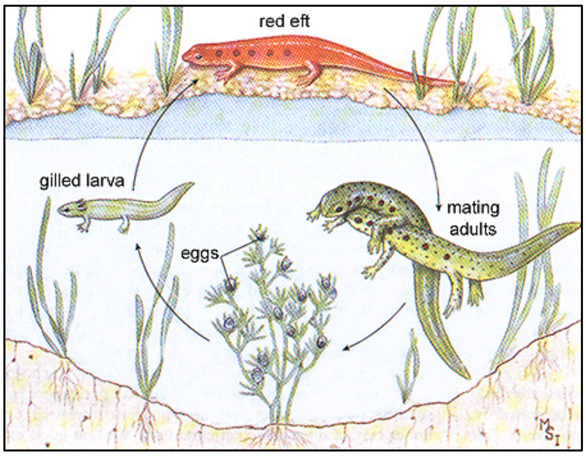
Topic 2.2 Adaptations for Gas Exchange – Page 2

		Completed
1.	Read page 2 and 3 about gas exchange surfaces in amphibians, birds and reptiles. • Complete the question on page 2	
2.	Label the human respiratory system on page 4.	
3.	Read and complete the activities on pages 5 to 8.	
4.	Read Toole and Toole 'Understanding Biology' page 399-403 Answer the following questions from Toole and Toole p410-411 Question 1; 2a,b and c only and 3.	

Gas exchange in other animals

Air has a higher concentration of oxygen compared to water. However, it is difficult keeping the respiratory surface moist in air. Most animals have adapted by having the respiratory surface deep in the body, such as the lungs in humans. In addition to minimising water loss it also helps to minimise heat loss.

Amphibians



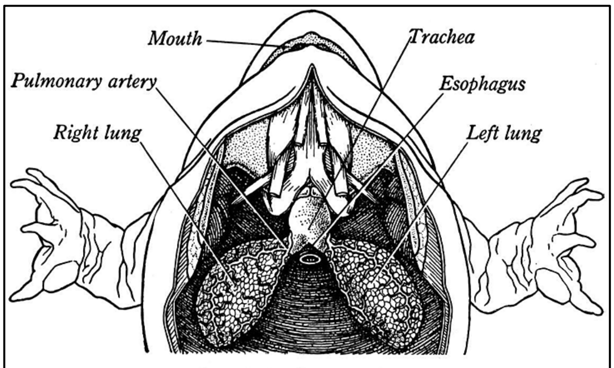
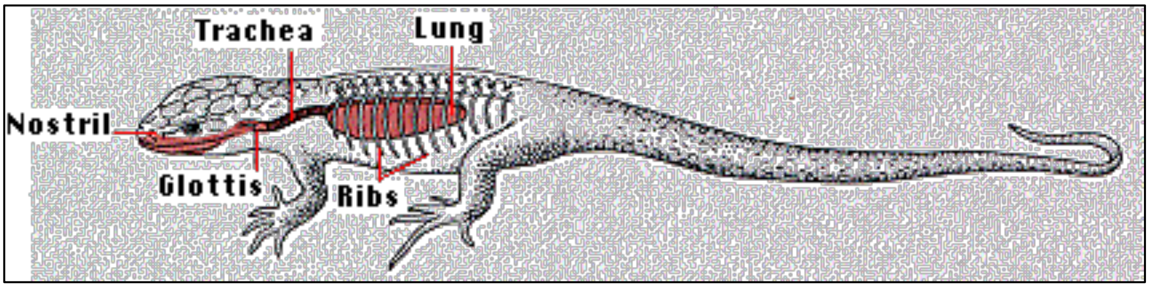


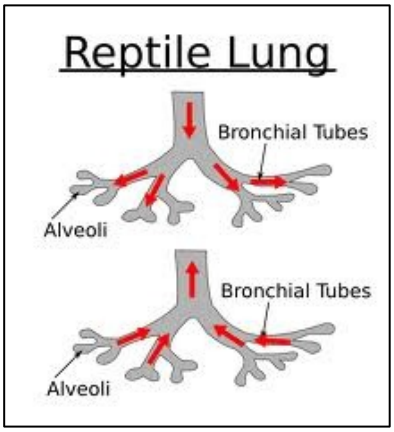
FIG. 388. *Lungs of Frog*

Amphibians have a larval form that is based in water. The larval form of amphibians uses gills. The adult form uses its moist skin as a respiratory surface whereas active adults will use lungs. The lungs of an adult are internal, simple and sac like.

Explain why the moist skin would not be able to supply the gas exchange needs of an active adult?

Reptiles

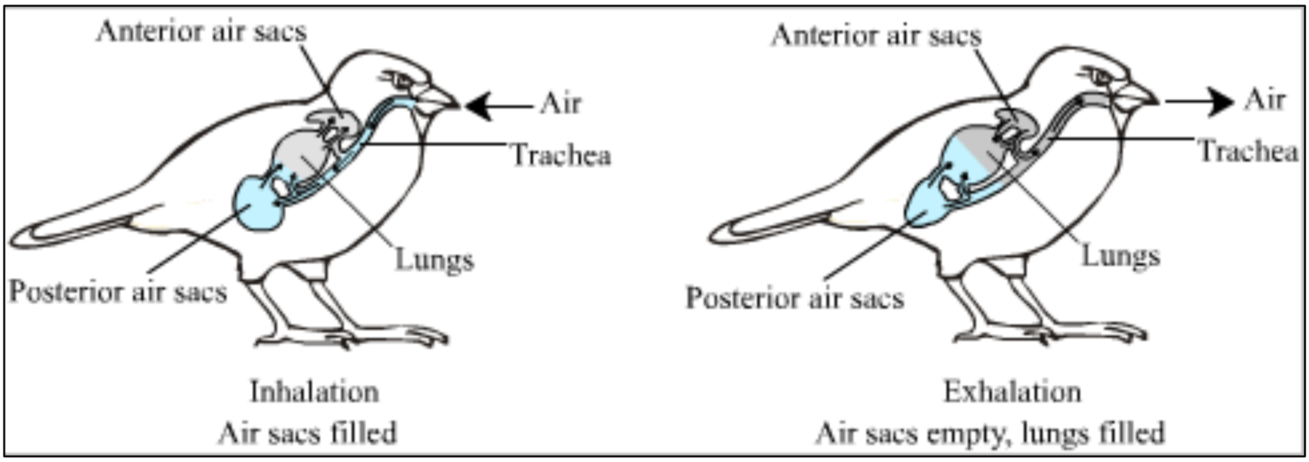




Reptiles have complex internal lungs which are protected by a rib cage. The rib cage and its associated muscles help with the ventilation of the lungs.

The lungs are more complex and folded compared to amphibian lungs, this helps with increasing the surface area for gas exchange.

Birds



Birds have lungs, but they also have air sacs. Depending upon the species, the bird has seven or nine air sacs.

Birds do not have a diaphragm; instead, air is moved in and out of the respiratory system through pressure changes in the air sacs. Muscles in the chest cause the sternum to be pushed outward. This creates a negative pressure in the air sacs, causing air to enter the respiratory system. Expiration is not passive, but requires certain muscles to contract to increase the pressure on the air sacs and push the air out. Because the sternum must move during respiration, it is essential that it is allowed to move freely when a bird is being restrained. Holding a bird "too tight" can easily cause the bird to suffocate.

Respiration in birds requires two respiratory cycles (inspiration, expiration, inspiration, expiration) to move the air through the entire respiratory system. In mammals, only one respiratory cycle is necessary.

The air sacs function like bellows pumping air into the lungs.

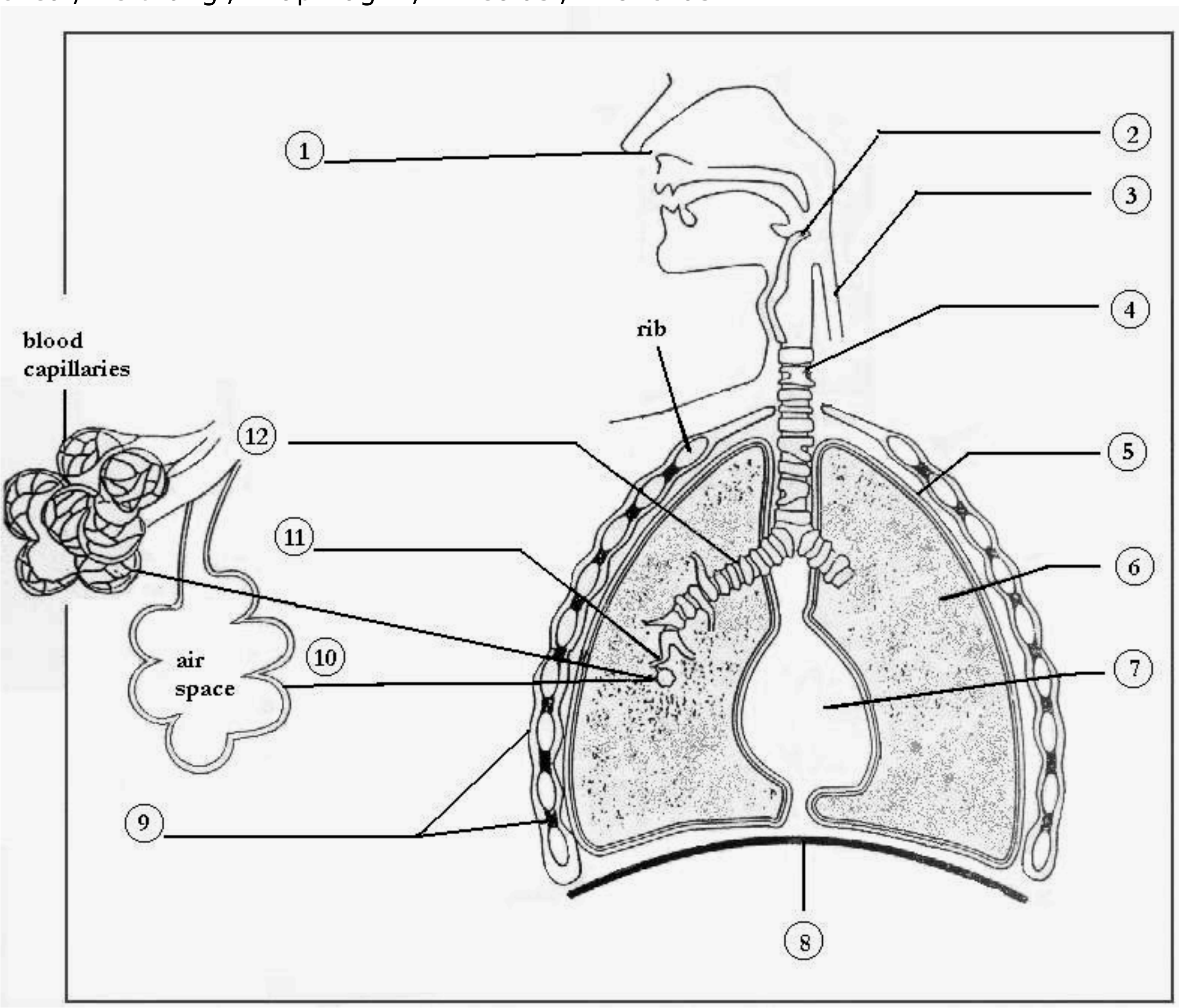
Human Respiratory System

In humans **muscular movements where air with a relatively high oxygen concentration is taken into our thoracic cavity and air with a relatively high carbon dioxide concentration is removed cause ventilation**. Oxygen and carbon dioxide diffuse into and out of the blood at the respiratory surfaces in the lungs; this is known as **gaseous exchange**.

Note: Chemical reactions in all living cells in which food is broken down to release energy using oxygen in the process is known as **respiration**, do not confuse this with gas exchange or ventilation!

The Structure of the Human Gas Exchange System

Air enters and leaves the body via the nose and mouth. It travels along a series of tubes to get to the lungs. The lungs are situated in the thorax (chest cavity). They are protected by the ribs and sternum (breastbone). Label the diagram below:
Nasal cavity / Gullet / Pleural membrane / Heart / Intercostal muscle / Bronchiole / Epiglottis / Trachea / Left lung / Diaphragm / Alveolus / Bronchus



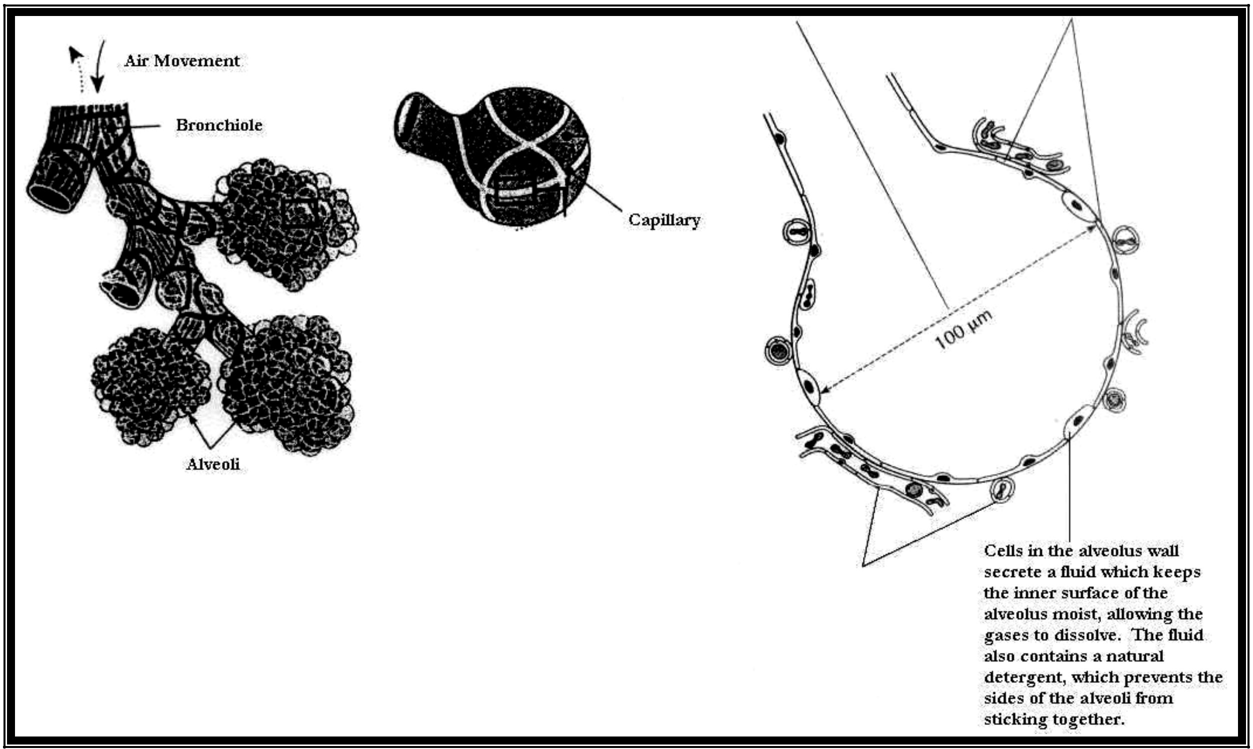
Each lung is surrounded by an air-tight cavity called the pleural cavity. This is bounded by two membranes, or pleura, which secrete pleural fluid into the cavity. The fluid is a lubricant, preventing friction when the lungs expand at inspiration. Pressure is always 500KPa lower than in the lungs and this allows them to expand and fill the thorax.

What is a more common name given to the larynx?

The alveoli are the delicate air sacs found at the end of the bronchioles and are the site for gas exchange.

Gas exchange is the transfer of gases between an organism and its environment. In humans oxygen is taken in and carbon dioxide is given out.

The alveoli need to be adapted so that gas exchange is quick and efficient. The diffusion distance between the inside of the alveolus and the bloodstream needs to be short. There needs to be a good blood supply to and from the alveoli which will help to maintain the concentration gradient for the two gases.



- On the right hand side diagram label the alveolus wall and the walls of three capillaries.

1. For gases to diffuse into or out of the blood, through how many cells do they have to diffuse?

____

Therefore the **diffusion distance is very short**, speeding up the exchange of gases.

2. A **dense network of blood capillaries** surrounds each alveolus. How will this help gas exchange?

____

Each capillary surrounding each alveolus is fed with blood coming from the pulmonary artery.

3. What can you say about the concentrations of oxygen and carbon dioxide in the blood?

____

4. Blood leaving the alveoli will feed into which blood vessel?

____

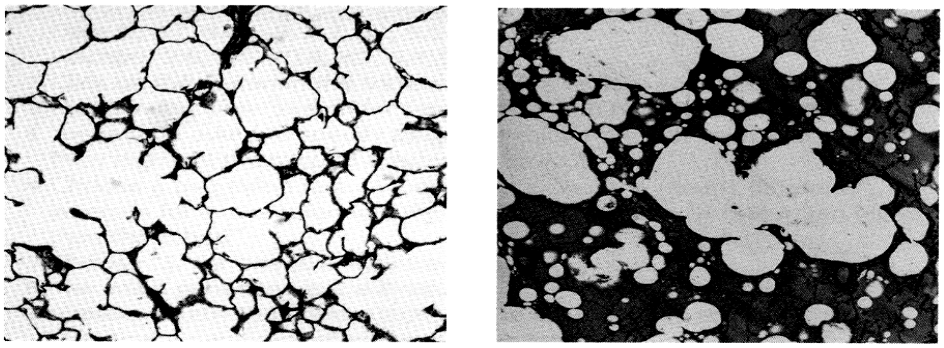
The maintenance of **high concentration gradients** for carbon dioxide and oxygen ensures efficient gas exchange.

The walls of the alveoli secrete a **detergent-like substance** that stops the alveoli sticking together when the lungs deflate.

There are millions of small alveoli in the lungs and these provide a **large surface area** for gas exchange.

Activity:

The figure below shows healthy lung tissue (left) and tissue from a lung with emphysema. They are both taken at the same magnification.



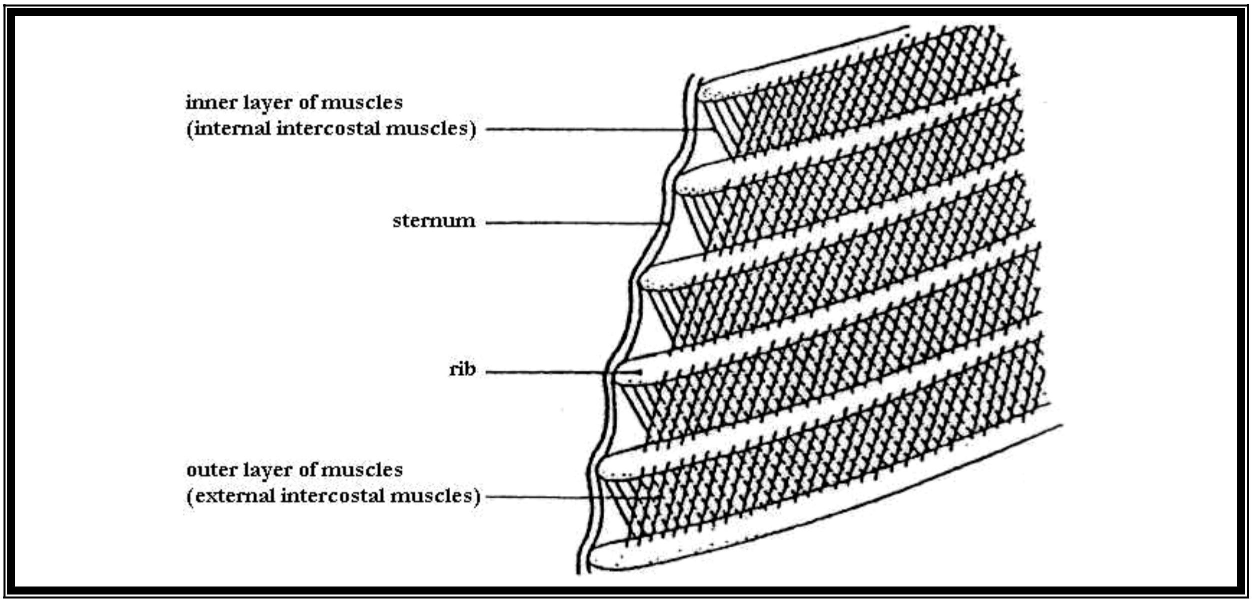
1. Place a ruler across each micrograph and count how many times the edge of the ruler crosses a gas exchange surface. Repeat this several times for each micrograph so that you can obtain comparable and meaningful results.

2. State your results using suitable units.

3. What conclusions can you make from your results?

5. Explain some of the symptoms you think would be felt by an emphysema sufferer.

Below is a simplified diagram of the muscles found between the ribs called the intercostal muscles. As with all muscles they work in pairs, as one contracts the other relaxes and vice versa.



1. Name the two antagonistic muscles:

____

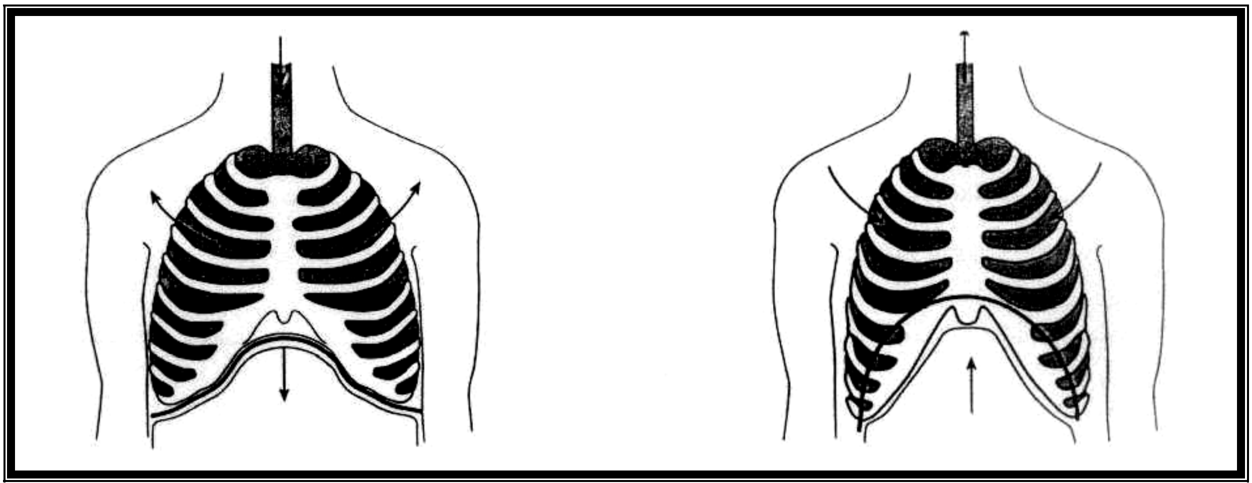
2. Looking closely at the diagram predict which way the rib cage will move when the external intercostal muscles contract.

____

3. Predict which way the rib cage will move when the internal intercostal muscles contract.

____

The diaphragm is a dome shaped tough sheet of connective tissue and is attached to the thoracic cavity by muscle. When this muscle contracts it becomes flatter..



4. Label the diaphragm muscle and the intercostal muscles on the previous diagrams.

If air is to be brought into the lungs then the air pressure inside the lungs has to be lower than the air pressure outside the lungs. If air is to be expelled from the lungs then the air pressure inside the lungs has to be higher then the air pressure outside the lungs.

These pressure changes are brought about by changing the volume of the thoracic (chest) cavity. If the volume is increased then the pressure will be decreased and vice versa.

The volume changes are brought about by the action of the intercostals muscles and the diaphragm muscle.

5. Look at the pairs of statements below and decide which goes into which column:

When we breathe in:	**When we breathe out:**

- External intercostal muscles contract / External intercostal muscles relax
- Internal intercostal muscles relax / Internal intercostal muscles contract
- Rib cage lifts up and out / Rib cage moves down and in
- Diaphragm muscle contracts / Diaphragm muscle relaxes
- Diaphragm becomes dome shaped / Diaphragm becomes flatter
- Volume inside the thoracic cavity increases / Volume inside the thoracic cavity decreases
- This causes air pressure inside the thoracic cavity to increase / This causes air pressure inside the thoracic cavity to decrease
- Air is drawn into the lungs to equalize the pressure difference / Air is forced out of the lungs to equalize the pressure difference

The Human Respiratory System

Lungs are internal sac-like organs found in most amphibians, and all reptiles, birds, and mammals. The paired lungs of mammals are connected to the outside air by way of a system of tubular passageways: the trachea, bronchi, and bronchioles. Ciliated, mucus secreting epithelium lines this system of tubules, trapping and removing dust and pathogens before they reach the gas exchange surfaces. Each lung is divided into a number of lobes, each receiving its own bronchus. Each bronchus divides many times, terminating in the respiratory bronchioles from which arise 2-11 alveolar ducts and numerous **alveoli** (air sacs). These provide a very large surface area (70 m^2) for the exchange of respiratory gases by diffusion between the alveoli and the blood in the capillaries. The details of this exchange across the **respiratory membrane** are described opposite.

Morphology of the Respiratory System

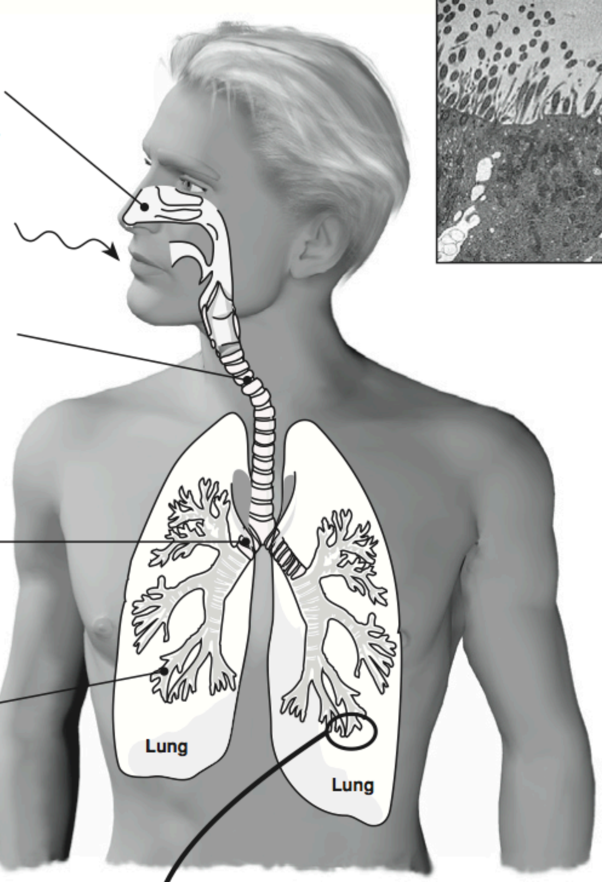
Nasal passages warm and moisten the air entering through the nostrils. Each nostril has a border of hairs to trap particles and filter them out of the system.

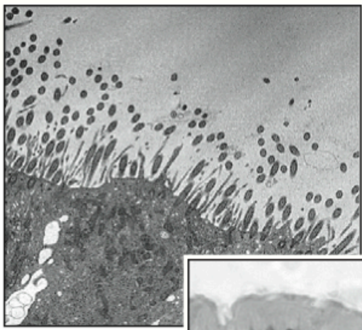
Air entering the body through the mouth enters the pharynx and mixes with air from the nasal passages.

The **trachea** lies in front of the oesophagus and extends into the thorax. It is strengthened with C-shaped bands of cartilage and lined with ciliated epithelium.

The trachea splits into two **bronchi**. These are also supported by cartilage bands.

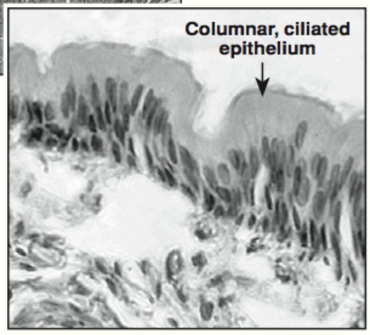
Bronchioles branch off the bronchi and divide into progressively smaller branches. The cartilage is gradually lost as the bronchioles decrease in diameter.





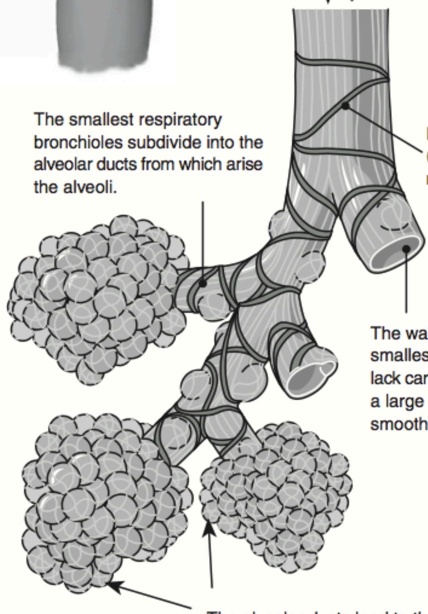
Photograph left: The nasal epithelium produces large amounts of mucus, seen here as droplets.

Photograph below: The epithelium of the trachea has many cilia. Mucus is produced from goblet cells.



Detail of a terminal bronchiole and its branches

Air movement

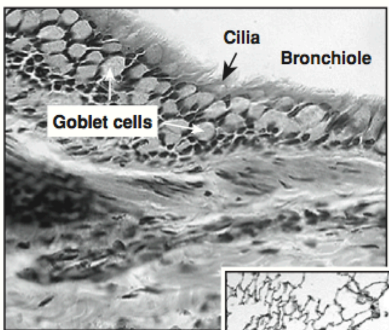


The smallest respiratory bronchioles subdivide into the alveolar ducts from which arise the alveoli.

Lymph vessels (blood vessels not shown)

The walls of the smallest bronchioles lack cartilage but have a large amount of smooth muscle.

The alveolar ducts lead to the alveoli. The alveoli tend to recoil inward (deflate) after each breath out. A phospholipid **surfactant** helps to prevent this by decreasing surface tension in the lung.



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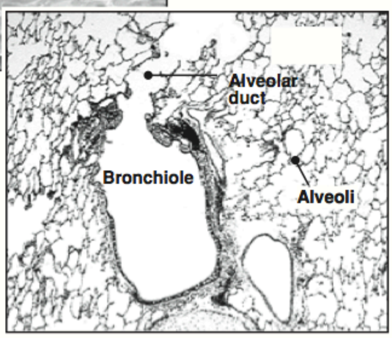
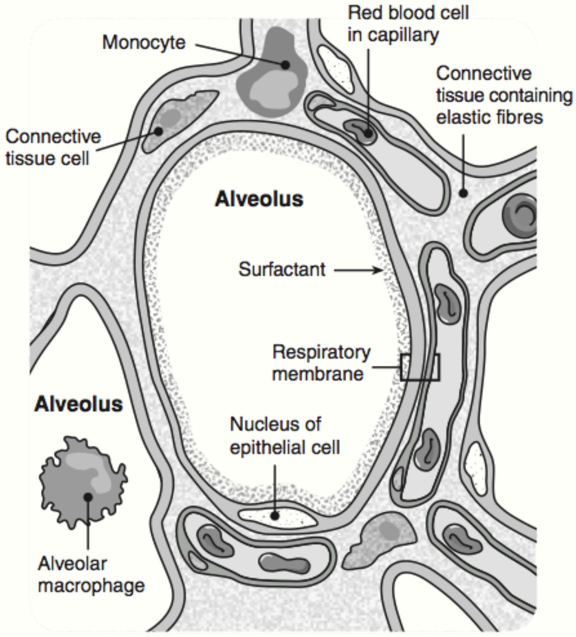
Photograph above: The epithelial lining of the bronchioles is ciliated and lined with mucus-producing **goblet cells**.

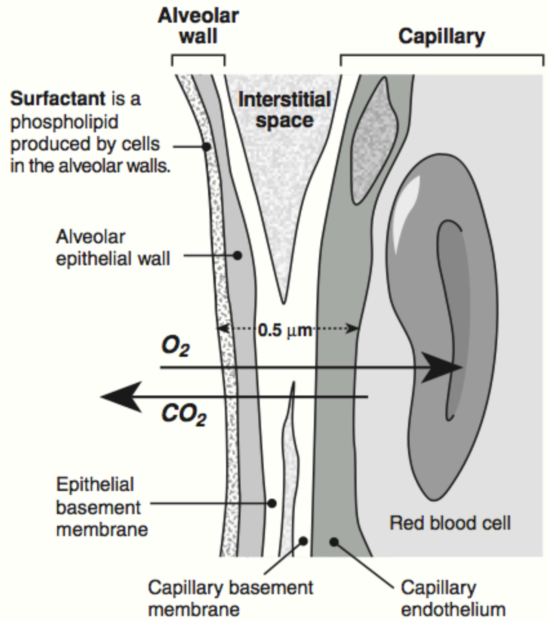


Photograph right: Respiratory bronchiole and alveolar duct leading to alveoli. Note the thin alveolar walls.

An Alveolus



The Respiratory Membrane



The diagram above illustrates the physical arrangement of the alveoli to the capillaries through which the blood moves. Phagocytic monocytes and macrophages are also present to protect the lung tissue. Elastic connective tissue gives the alveoli their ability to expand and recoil.

The **respiratory membrane** is the term for the layered junction between the alveolar epithelial cells, the endothelial cells of the capillary, and their associated basement membranes (thin, collagenous layers that underlie the epithelial tissues). Gases move freely across this membrane.

(a) Explain how the basic structure of the human respiratory system provides such a large area for gas exchange:

___

___

(b) Identify the general region of the lung where exchange of gases takes place: ___

Describe the structure and purpose of the respiratory membrane: ___

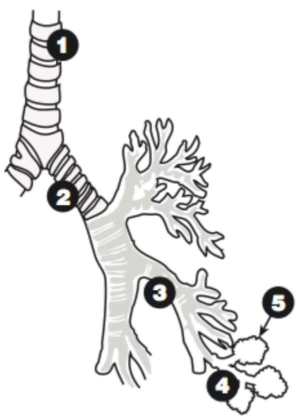
___

___

Describe the role of the surfactant in the alveoli: ___

___

Using the information above and opposite, complete the table below summarising the **histology of the respiratory pathway**. Name each numbered region and use a tick or cross to indicate the presence or absence of particular tissues.



	Region	Cartilage	Ciliated epithelium	Goblet cells (mucus)	Smooth muscle	Connective tissue
1						✓
2						
3		gradually lost				
4	Alveolar duct		✗	✗		
5					very little	

Babies born prematurely are often deficient in surfactant. This causes respiratory distress syndrome; a condition where breathing is very difficult. From what you know about the role of surfactant, explain the symptoms of this syndrome:

___

___

Bio Factsheet
Number 26

Gas Exchange in Animals

All living organisms respire. They need to do this so that energy can be transformed into a form that cells can use. In aerobic respiration, oxygen is used by cells and carbon dioxide is a waste product. In anaerobic respiration, although oxygen is not used, carbon dioxide is still a waste product. Gas exchange is the diffusion (passive movement) of these gases into and out of cells and it is essential for respiration to take place.

For gas exchange to occur efficiently, organisms require:

- a **large surface area** over which gas exchange may take place rapidly
- a **concentration gradient** down which gases may diffuse
- a **thin surface** across which gases may diffuse rapidly
- a **moist surface** on which gases may dissolve and diffuse into and out of cells

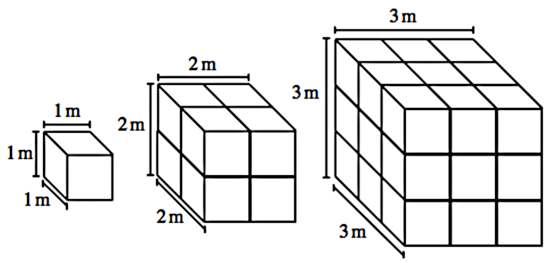
Such surfaces are called **gas exchange surfaces**.

This Factsheet will discuss how living organisms achieve gas exchange and each of the examples given will make reference to the four points above.

Unicellular organisms

The gas exchange surface of unicellular (single-celled) organisms is the cell surface membrane. Although this is not a specialised gas exchange surface (as in the case of many multicellular organisms) it achieves efficient gas exchange because it has a large surface area to volume ratio. Fig 1 demonstrates how the surface area to volume ratio of a cube decreases as its volume increases. The same is true of living organisms. The small size of unicellular organisms means that they have a large surface area over which gas exchange may take place. In other words, the smaller the organism, the greater its surface area to volume ratio and the greater the efficiency of diffusion of gases through the outer cell surface membrane.

Fig 1. Surface area to volume ratios of differently sized cubes



surface area	$6m^2$	$24m^2$	$54m^2$
volume	$1m^3$	$8m^3$	$27m^3$
surface area: volume	6:1	3:1	2:1

The build up of carbon dioxide inside a respiring unicellular organism sets up a concentration gradient so that the gas diffuses out of the cell. If the organism respires aerobically then oxygen diffuses down a concentration gradient into the cell as the oxygen is used up.

The cell surface membrane of unicellular organisms is thin ensuring rapid gas exchange and it is moist to allow gases to dissolve.

Multicellular organisms

Most multicellular organisms respire aerobically. This is because the energy requirements of multicellular organisms tends to be great and aerobic respiration provides nineteen times more ATP (Adenosine triphosphate) per molecule of glucose respired than anaerobic respiration. Multicelluar organisms therefore require an efficient supply of oxygen so that their energy needs can be met.

To achieve efficient gas exchange, multicellular organisms have large gas exchange surfaces. In small multicellular organisms the outer surface of their bodies is usually sufficient. Larger multicellular organisms require specialised surfaces such as lungs or gills.

Maintaining a concentration gradient for gases is a problem that large organisms face because diffusion becomes less efficient over larger distances. Transport systems (e.g. circulatory systems) are needed to ensure that dissolved gases can move to and from respiring tissues rapidly.

Terrestrial (land-living) organisms often have internal gas exchange surfaces to reduce evaporation losses. The following examples illustrate some of the gas exchange surfaces of animals.

Animals without specialised gas exchange surfaces

Many small terrestrial animals use their outer body surfaces efficiently for gas exchange. The earthworm, *Lumbricus terrestris*, achieves this with:

- an elongated body to increase surface area to volume ratio
- a primitive circulatory system to maintain a concentration gradient
- a moist outer body surface

The outer body surface of the earthworm is supplied with a dense capillary network, which join up to form contractile blood vessels. The earthworm does not contain a heart but the circulatory system transports oxygen to and carbon dioxide away from respiring tissues, thereby increasing the efficiency of diffusion.

Animals with specialised gas exchange surfaces

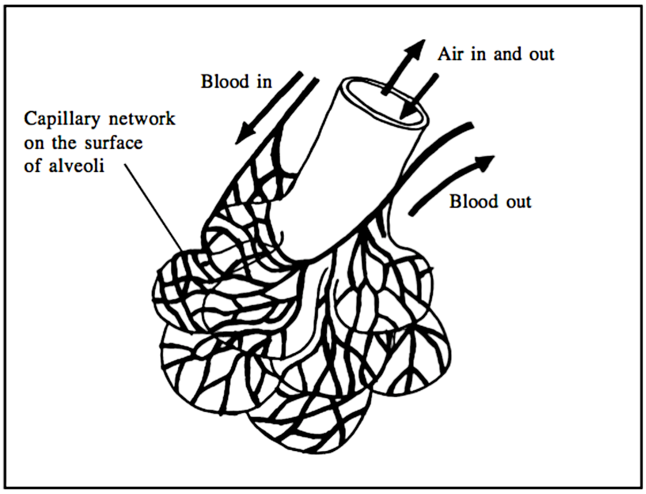
Mammals

Mammals are examples of large terrestrial animals. They do not rely on their outer body surface for gas exchange but have specialised internal gas exchange surfaces, called lungs, which have the following features:

- a large surface area due to numerous air sacs called alveoli
- a highly developed circulatory system
- a short distance between alveoli and the circulatory system ensuring rapid diffusion across the gas exchange surface
- the surface of the alveoli is covered by a thin layer of fluid

Fig 2 shows a diagram of a human alveolus. Note the numerous capillaries and their close proximity to the gas exchange surface.

Fig 2. The alveoli



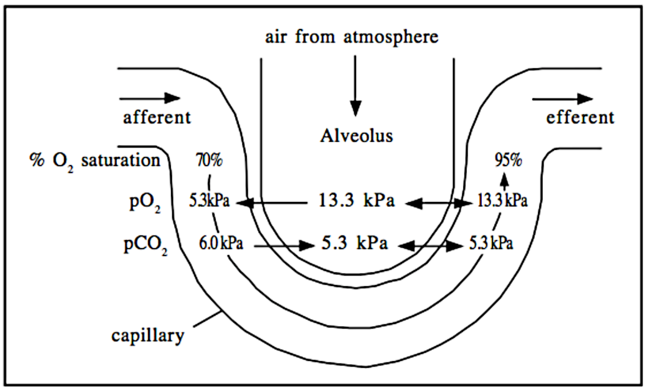
The concentration gradients of carbon dioxide and oxygen in the alveoli are maintained by the highly efficient blood transport of the capillaries surrounding each alveolus and by **ventilation** (breathing), which ensures that air moves in and out of the lungs regularly. Diffusion becomes less efficient over larger distances, so the transport system prevents the build up of carbon dioxide or oxygen, thus maintaining the necessary concentration gradient. Red blood cells contain the protein haemoglobin, which associates strongly with oxygen and carbon dioxide providing greater efficiency.

The partial pressures of oxygen (pO_2) and carbon dioxide (pCO_2) at the gas exchange surface, show how the concentration gradient is established (Fig 3).

Partial pressure is a way of expressing the concentration of a gas and is measured in kilopascals (KPa).

e.g. Oxygen represents about 21% of the atmosphere.
The total pressure of the atmosphere is 101.3KPa.
The partial pressure of oxygen (pO_2) is therefore 21% of 101.3KPa, which is 21.2KPa.

Fig 3. The partial pressures of oxygen and carbon dioxide in the alveoli



Oxygen inside the lungs has a partial pressure (pO_2) of 13.3KPa. This is less than the pO_2 in the atmosphere because the inhaled air has mixed with the air already in the lung (residual air) which has a lower pO_2. Blood in capillaries travelling towards the alveoli (afferent capillaries) has a pO_2 of about 5.3kPa. There is therefore a concentration gradient between the oxygen in the alveoli and oxygen in the capillaries and oxygen diffuses into the capillary. The blood travelling away from the alveoli (efferent capillary) has a pO_2 of 13.3KPa, thus equilibriating with oxygen inside the alveolus.

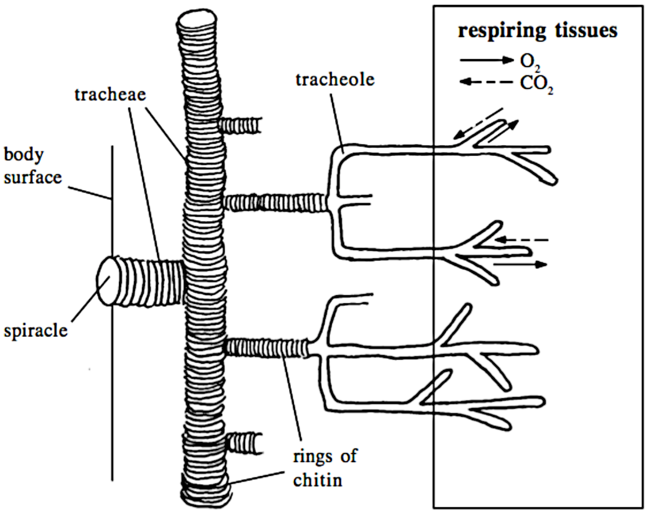
The converse is true of carbon dioxide. The pCO_2 in afferent capillaries is 6.0kPa, which is higher than the pCO_2 inside the alveoli because the blood is carrying carbon dioxide produced by respiring tissues. A concentration gradient is set up so that carbon dioxide diffuses into the alveolus. The efferent capillary has a pCO_2 of 5.3kPa (the same as the pCO_2 of the alveolus). Therefore, the carbon dioxide inside the capillary and alveolus have also reached equilibrium.

Insects

The hard exoskeleton of insects is unsuitable for gas exchange but their internal gas exchange surfaces differ significantly from those of mammals. The most significant difference is the lack of a transport system.

Fig 4 shows a diagram of the insect's gas exchange surface. Note that the tracheoles join up to trachea. The trachea lead to the outside via pores on the insect's outer body surface (spiracles).

Fig 4. The insect tracheal system



The main features of insect gas exchange are:

- a large surface area achieved by an extensive network of tubes (tracheoles) which penetrate deep into tissues
- small bodies which enable gases to get in and out of tissues by diffusion alone, in some cases aided by rhythmical body movements
- thin, fluid filled tracheoles which allow gases to dissolve and diffuse into tissues efficiently

The extensive network of tracheoles in the gas exchange system of the insect resembles the mammalian circulation system. Gases diffuse passively through the spiracles, trachea and tracheoles directly to the tissues. Some species of insect produce rhythmical muscle contractions to assist the passive diffusion of gases. This is a type of ventilation.

Insects can control their rate of gas exchange. When respiration levels are high, the concentration of lactic acid in tissues increases. This sets up an osmotic pressure causing fluid to diffuse from the tracheoles into the tissues by osmosis. Gas exchange then occurs more rapidly because the gases can diffuse at a faster rate through a gaseous medium (the residual air in the tracheoles) rather than a liquid medium.

Fish

Fish use water as a gas exchange medium instead of air. The properties of both media are summarised in Table 1.

Table 1. Properties of air and water as gas exchange surfaces

	Air	Water
pO_2	21.1	1.0
Stability of pO_2	Stable with temperature changes	Decreases with increasing temperature
Diffusion rate (arbitrary units)	10 000	1
Gas exchange surface needs supporting	Yes	No
Oxygen dissolved	No	Yes
Density (arbitrary units)	1	777
Viscosity (arbitrary units)	1	100

Fish rely on specialised flaps of tissue called gills for gas exchange. Gills may be external or internal (see Fig 5). External gills usually have a higher surface area but they are less protected.

Fig 5. Schematic diagrams of internal and external gills

The gas exchange surface of fish has the following features:

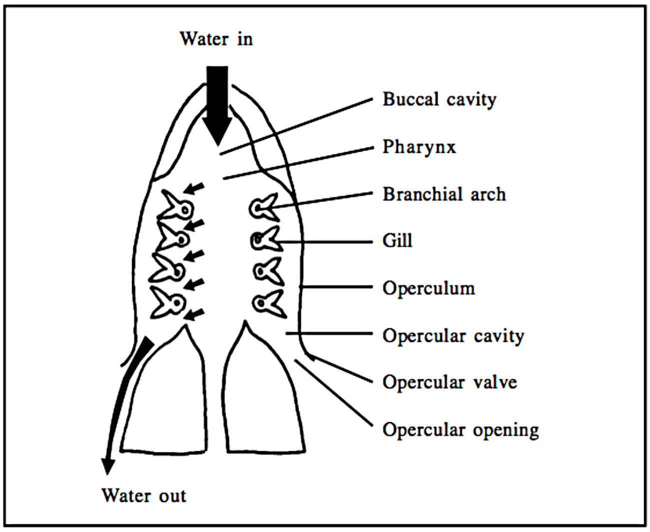
- gills have numerous folds which give rise to a large surface area
- the concentration gradient is achieved by an efficient circulatory system

Ventilation of gills

External gills receive oxygen passively from the surrounding water. Internal gills however, are protected by an operculum (Fig 6) and therefore need to be actively ventilated. The fish takes water in through its buccal cavity which then flows through the pharynx and past the gill plates, leaving via the opercular openings on each side of the fishes head.

Internal gills are ventilated as shown in Fig 6:

Fig 6. Ventilation of internal gills



Parallel and counterflow mechanisms of gas exchange

Water which comes in contact with the gills may flow in the same direction as blood in the gill capillaries - parallel flow, or it may flow in the opposite direction - counterflow.

In the parallel flow mechanism, the pO_2 of the blood in the efferent capillaries is about 50% of that of the water entering the buccal cavity of the fish. In other words, the pO_2 of the blood and the water leaving the gills are the same and there is no longer a concentration gradient.

In the counterflow mechanism, the pO_2 of the blood in the efferent capillaries is nearly 100% of that of the water entering the buccal cavity of the fish. This mechanism therefore maintains a concentration gradient between the water and the blood in the capillaries even when the blood is highly saturated with oxygen.

The counterflow mechanism is much more efficient because it ensures that there is always a diffusion gradient between the water which is flowing through the gill lamellae and the blood in the lamellae. As blood flows through the gill lamellae, it therefore absorbs more and more oxygen until the pO_2 of the blood is almost the same as the pO_2 of the incoming water. By the time the water leaves the gills it has lost almost all of its oxygen to the blood. This mechanism therefore results in the pO_2 of the water exceeding the pO_2 of the blood across the entire gill plate and this ensures that a concentration gradient is maintained. Fig 7 shows the oxygen saturation of the blood and water across the gill plate in both the parallel flow and counterflow mechanisms.

Fig 7. Parallel and counterflow mechanisms of ventilation in fish

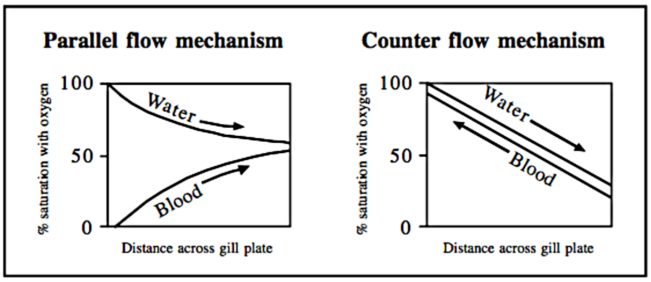


Table 2. Summary of gas exchange surfaces

Size of organism	Example	Gas exchange surface	Mechanism of gas exchange
Unicellular	Amoeba	Outer cell surface	Diffusion
Multicellular	Earthworm	Outer body surface	Diffusion
Multicellular	Mammal	Alveoli	Diffusion, ventilation and circulatory system
Multicellular	Insect	Junctions between tracheoles and respiring tissues	Diffusion (and ventilation in some species)
Multicellular	Fish	Gills	Diffusion ventilation and circulatory system

Practice Questions

1. Very small organisms such as the amoeba do not have specialised gas exchange systems. Mammals are large, multicellular organisms and have a complex gas exchange system. Explain why the mammal needs such a system when the amoeba does not. (4 marks)

2. Bony fish rely on gills for gas exchange.

   (a) Why does the highly folded structure of the gills increase the efficiency of gas exchange? (2 marks)

   (b) Explain how the counterflow mechanism works in bony fish. (3 marks)

   (c) Suggest why gill lamellae would not provide an efficient gas exchange surface on land. (2 marks)

3. Name two similarities and two differences between the gas exchange of an insect and that of a mammal. (4 marks)

Answers

Semicolons indicate marking points.

1. The amoeba has a large surface area to volume ratio/and a short diffusion pathway to all parts of the organism;
   therefore diffusion is efficient;

   The mammals have a small surface area to volume ratio, a long diffusion pathway and they have skin which is waterproof and gastight;
   they need an internalised system so that the gas exchange surface can be kept moist/the folded surface of the lungs provides a large surface area;

2. (a) Increases surface area;
   over which diffusion may take place;

   (b) The blood flows in the opposite direction to the water across the gills;
   as a result, highly oxygenated water comes into contact with poorly oxygenated blood;
   this maintains (an oxygen) concentration gradient across the whole of the gill plate/maximises diffusion;

   (c) The gills may dry out;
   thus preventing oxygen dissolving on the surface of the gills;
   they are no longer supported by water/folds may stick together with surface tension/not open as easily;

3. Similarities:
   large surface area;
   moist gas exchange surface;
   thin gas exchange surface;
   concentration gradient achieved by ventilation (in some species of insects);

   Differences:
   Transport (circulatory) system in mammals but not in insects;
   the respiratory surface in mammals is the alveoli, in insects it is the junction between the tracheoles and the respiring tissues;

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